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Dosimetric considerations for environmental radiation and NORM

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Abstract. The physical theory of dosimetry for environmental radiation, including radiation emitted from naturally occurring radioactive materials (NORM), is no different than that required in any other setting where doses are estimated. However, the application of such theory to environmental radiation and NORM may require considerations that differ from dose estimation elsewhere. This is especially true if the intent is to provide estimated doses for epidemiologic analyses. It should be realized that metrics of radiation dose for radiation protection purposes are generally not the same as for analytic epidemiologic studies which require estimates of absorbed dose to specific organs of identified persons. In addition, exposures to environmental radiation and NORM typically involve radiation fields that vary considerably over space, and the patterns of an individual's movements, as well as the types of buildings in which they reside and work, can significantly affect the dose received from external radiation. Realistically describing the spatial variation of environmental exposure rates is a difficult challenge for environmental dosimetry, rather than the physical principles that are relatively well understood. This publication will review these ideas in the context of improving estimated doses from high background radiation studies.

Keywords: Dose; Dosimetry; Natural background radiation; NORM; Epidemiology

1. Introduction

Radiation doses from ionizing radiation in areas of the world with high natural background radiation (HNBR) have been reported for several decades. However, the publications over the years have reported "dose" in terms of various metrics including exposure, dose equivalent, equivalent dose, effective dose equivalent, and effective dose. Similarly, many publications have not carefully defined whether the reported "dose" was

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intended to represent dose to air, dose to a specific tissue/organ or the whole body, dose to a representative person, or dose to an identified person. Lack of clarity regarding the definition of reported "doses" makes comparison of the findings from different studies difficult. Moreover, in some cases, improper dose units have been used to infer epidemiologic conclusions.

It is clear that different types of investigations may require different metrics of dose and different levels of detail to assess dose. The range of detail included in dose estimation can extend from simple to relatively complex, depending on whether the goal is simple documentation of the air kerma at a specific location or an estimation of the organ absorbed dose received by identified persons. Dose estimation in studies of HNBR should include both external and internal dose where relevant, though due to space considerations, discussion in this paper is limited to external dose.

It is the purpose of this paper to discuss issues relating to choice of an appropriate metric of radiation dose and the means to obtain external doses to specific organs, particularly for studies of HNBR. These considerations can be used to advance the quality of estimated doses towards the level required for analytic epidemiologic studies.

2. Discussion

2.1. Choice of metric of radiation exposure

Though there is little discussion in the literature about requirements of dosimetry for epidemiologic purposes, the International Commission on Radiological Protection has long noted that "Both equivalent dose and effective dose are quantities intended for use in radiological protection, including the assessment of risks in general terms. . .For estimation of the likely consequences of an exposure of a known population, it will sometimes be better to use absorbed dose. . .relating to the exposed population" [1]. Moreover, the U.S. National Academy of Sciences reviewed criteria to be considered in dose reconstruction for epidemiologic uses [2] and concluded that dose estimates should be reported as annual organ absorbed doses from both low-LET and high-LET radiation. Because radiation- and tissue-weighting factors for equivalent dose and effective dose have been developed for radiation protection, rather than for research purposes, and because those factors are subject to change over time, research studies to quantify health risks are better served by estimates of absorbed dose to specific organs. Investigators with an interest in the relationship between high background radiation exposure and health risks should seriously consider estimating organ-specific absorbed doses (Gy) on the basis of identified individuals.

2.2. Instrument "dose" to organ dose

In this discussion, only two types of measurements will be discussed: (1) measurements of dose rate or time-integrated dose in air, and (2) measurement of time-integrated dose on the body of individuals. The first technique might be accomplished by various types of meters and detectors such that the instrument does not receive significant backscatter from a person's body and does not significantly perturb the radiation field. The second technique might be accomplished by an integrating dosimeter (e.g., TLD, film badge, etc.) attached to the body of a person with the intention that the detector receives backscatter from the body.

"In air" measurements may be reported by an instrument in a variety of metrics and units, depending on the calibration of the device: Roentgen s^{-1}, rad s^{-1} or rem s^{-1}, or mGy s^{-1} or mSv s^{-1}. In this case, the measurement pertains to a point in space even if the device is calibrated in absorbed or equivalent dose. The measurement represents, at best, a dose or dose rate that might be received at that specific location.

"On body" measurements are generally reported as a form of equivalent dose (*personal dose equivalent* refers to a calibration on an ICRU slab of a specified depth, generally 10 mm). Here, the measurement includes scattered radiation typical of the body and reflects an integration of the dose rates experienced as the individual moves throughout a spatially varying radiation field.

The value of "in air" or "on body" measurements will depend on their purpose, though neither are the preferred quantity for epidemiological studies, i.e., absorbed dose to specific organs [1]. "In air" or "on body" measurements can be used to derive organ doses, however, different calculations and assumptions are necessary. If exposure rate is measured (e.g., by a pressurized ionization chamber) and expressed in units of C kg^{-1} s^{-1}, the measured value is directly related to the air kerma rate (ignoring the small correction for radiative losses) through W/e, the mean energy required to form an ion pair in air. In that case, the absorbed dose to a specific organ or tissue can be estimated as:

$$D_T = \dot{X}t(W/e)(D_T/K_a) \quad (1)$$

where, D_T=tissue absorbed dose (Gy), $\dot{X}$=exposure rate (C kg^{-1} s^{-1}, where 1 R s^{-1}=2.58×10^{-4} C kg^{-1} s^{-1}), t=time (s) spent at location with exposure rate as described, W/e=mean energy expended in air to form an ion pair $\cong$ 34 J/C, K_a=air kerma (Gy).

If an "on body" measurement is reported, where the detector has been calibrated to the ICRU slab, the reported *personal dose equivalent* may be converted to air kerma and the organ absorbed dose estimated:

$$D_T = H_p(10)\left[K_a/H_p(10)\right](D_T/K_a) \quad (2)$$

where $H_p(10)$=personal dose equivalent (mSv).

Representative values of the coefficients for Eqs. (1) and (2) are provided in Table 1 [3]. The values presented are for a rotationally symmetric exposure geometry and for three energies: (i) 0.186 MeV (energy of the primary gamma ray emitted by ^{226}Ra), (ii) 0.43 MeV (average energy of the ^{238}U chain in equilibrium), and (iii) 0.64 MeV (average energy of the ^{232}Th chain in equilibrium).

Table 1
Coefficients [3] for estimating absorbed organ doses in high background studies

Source	Average gamma energy (MeV)	Air kerma per unit $H_p(10)$[a] (Gy Sv^{-1})	Organ dose per unit air kerma[b] (Gy Gy^{-1})			
			Red bone marrow	Breast	Lung	Thyroid
Ra-226	0.186	0.66	0.84	0.89	0.91	1.14
U-238 chain (in equil.)	0.43	0.78	0.79	0.85	0.86	1.03
Th-232 chain (in equil.)	0.64	0.82	0.79	0.86	0.86	1.02

[a] $[K_a/H_p(10)]$ in Eq. (2).
[b] $[D_T/K_a]$ in Eqs. (1) and (2).

2.3. Increasing realism of external dose estimations

Estimates of absorbed (external) dose to specific organs of individuals, as required by epidemiologic studies, must account for the dose obtained both in and outdoors by accounting for the air kerma rate at all locations where an individual spends significant amounts of time as well as the proportions of time spent at each location. It is well known that when indoors, the building can provide shielding against radiation emitted from the soil; however, the building can potentially contribute to the external dose if it is made from earthen materials derived from a HNBR area. To add necessary realism to the estimated external dose for an individual, Eq. (1) can be rewritten in the form of a summation of exposure rates at all locations where time is spent (assuming here that only a single choice of the energy dependent ratio, $[D_T/K_a]$, is needed).

$$D_T = \left[\sum_{i=1}^{n} \dot{X}_{\text{indoors},i} t_{\text{indoors},i} + \sum_{j=1}^{m} \dot{X}_{\text{outdoors},j} t_{\text{outdoors},j} \right] (W/e)(D_T/K_a) \tag{3}$$

where i refers to indoor locations with significantly different exposure rates, j refers to outdoor locations with significantly different exposure rates, $\dot{X}$=exposure rate (C kg^{-1} s^{-1}) either indoors or outdoors, $t_{\text{inside},i}$ refers to the number of seconds per day spent indoors at location i, $t_{\text{outside},j}$ refers to the number of seconds per day spent outdoors at location j.

3. Concluding remarks

While knowledge about HNBR areas has increased substantially over the years [4], estimation of doses in many studies still needs to be improved for several reasons. First, imprecise definitions of the metric and improper units of reported “doses” can lead to confusion and error in making comparisons among different sites. The definitions of weighted dose metrics, e.g., *effective dose* [1], are subject to change over time and include modifying (weighting) factors to the absorbed dose that are not relevant when performing analytic epidemiologic studies designed to determine health risks. Estimates of absorbed dose to specific organs for individuals are necessary for epidemiologic analyses and can be made from measurements of exposure, air kerma, or personal dose equivalent. Increased realism in organ dose estimates can be accomplished by properly accounting for spatial variations in the radiation field including the differences in air kerma rate indoors and outdoors and the time spent at each location, or by obtaining measurements from personal radiation monitoring devices worn by individuals.

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